P-11

NASA Technical Memorandum 102381

Nonlinear Combustion Instability Model in Two- to Three-Dimensions

(NASA-TM-102381) NONLINEAR COMBUSTION INSTABILITY MODEL IN TWO- TO THREE-DIMENSIONS (NASA) 11 p CSCL 21H

N91-31208

Unclas

G3/20 0038302

Richard J. Priem
Priem Consultants, Inc.
Cleveland, Ohio

and

Kevin J. Breisacher
Lewis Research Center
Cleveland, Ohio

Date for general release October 1991

Prepared for the
26th JANNAF Propulsion Meeting
Pasadena, California, October 23-27, 1989

E-5097

NONLINEAR COMBUSTION INSTABILITY MODEL IN TWO- TO THREE-DIMENSIONS

Richard J. Priem
Priem Consultants, Inc.
13533 Mohawk Trail
Cleveland, Ohio 44130

and

Kevin J. Breisacher
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

A model is developed based on using "quasi-steady state" equations for the injection, atomization and vaporization processes that consider the instantaneous local pressures, temperatures, density and gas velocity vector associated with a three-dimensional wave. The coupled sets of equations are solved to determine frequency and growth rate of the oscillations as a function of wave amplitude. Calculated results are used to explain the observed instabilities in a 40 Klb LOX/Methane combustor.

INTRODUCTION

Nonlinear instabilities (oscillations that require a finite amplitude disturbance to initiate and then rapidly increase in amplitude) are frequently observed in liquid rocket engines. Recently[1] instabilities in a 40 Klb LOX Methane combustor were observed that had a dramatic change in frequency as the amplitude of the oscillations increased.

To explain these phenomena and to enhance the modeling capability for liquid rocket engines, a nonlinear model is required that physically models the various processes occurring in the combustion chamber. Many models are available that use simplifying assumptions to make them linear. The objective in developing the model described herein was to use the same physical models used in previous studies, without the simplifying linear assumptions. Another goal was to include the interaction effects between different physical processes.

The model uses the major nonlinear and interaction terms except for using the wave equation with separation of variables to describe the oscillations in the combustion chamber instead of using a full three-dimensional CFD code to solve the conservation equations. Only a brief description of the model can be provided in this paper, a more detailed report describing all the features with a listing of the program will be published later.

As a first attempt to validate the model, calculated results for the 40 Klb LOX Methane engine are provided to show the models capability to describe the observed influence of wave amplitude. Stability limits for this engine are also matched to the experimental data to indicate the influence of design and operating variables on instability.

THEORY

Of the five processes involved in combustion instabilities, as identified by the JANNAF Workshop on Combustion Instability Mechanisms (Injector coupling, Atomization, Vaporization, Mixing and Wave Dynamics), all but the Mixing process were included. Each will be briefly described. Mixing of fuel and oxidizer was assumed to be relatively fast, and since detailed equations are not available (other than a complete three-dimensional CFD code) to calculate the local-instantaneous mixing rates, this process was not considered. All the equations were expanded in a Fourier series for time dependency. Only the oscillations associated with the fundamental frequency in the expansion were calculated in this study. The program can be expanded to determine harmonic components.

INJECTION COUPLING

Flow oscillations, produced by chamber pressure oscillations, in both the fuel and oxidizer injector elements were modeled. Oscillations in the manifolds were described by the three-dimensional wave equation using separation of variables. The three-dimensional equation can be simplified to a lumped parameter model or an axial wave in the manifold. Normally the calculations are made with the same eigen value mode for both the manifold and the combustor.

Flow and pressure oscillations in the tubes of a coaxial injector were determined by solving the one-dimensional time dependent conservation equations as a function of axial position. This included pressure losses associated with an office area change. Via this technique, the response of flow oscillations to chamber pressure (for the fundamental frequency) is obtained. For finite amplitude oscillations, the local pressure and velocity can reach minimum/maximum values associated with the saturation pressure of the fluid and sonic velocity. When these occur the solutions are not valid. For chamber pressure oscillations higher than those that produce saturation or sonic velocity conditions, the response is reduced by the square root of the limit chamber pressure oscillation to actual pressure amplitude.

ATOMIZATION

The atomization process is followed on a quasi-steady basis using the Mayer theory[2] for coaxial injection. The instantaneous local velocities are determined at various times in an oscillation cycle. The atomization rate and drop size produced in the recess and combustion chamber are calculated for conditions corresponding to these velocities. In the recess of the coaxial element, the fuel is allowed to expand to the area between the outside diameter of the recess and the diameter of the oxidizer stream. The velocities are assumed to be constant in the recess. Downstream of the recess the fuel is allowed to expand in a cone with a constant cone angle (normally 15° half angle). If a chamfer is present on the oxidizer tube, the oxidizer can expand to any diameter in the chamfer, but normally it was assumed to have full expansion.

The drop size formed by the spray was specified as the mass average of drops produced at various locations. An effective atomization plane was established at the median for mass removed from the jet. If the median is inside the recess, the atomization plane is at the injector face. Vaporization was assumed to start at the effective atomization plane. The drop size distribution can be represented by 1 to 21 drops of different sizes. Normally 11 drop size groups were used for steady state performance calculations and 5 drop size groups were used for instability calculations. With 5 drop size groups each size has 20 percent of the total mass flow rate and the drops are assumed to follow a 1.53 distribution.[3]

VAPORIZATION

The quasi-steady vaporization theory of Ref. 3 was used to calculate the burning rate of individual drops as a function of distance and thereby time. Injection of individual drops occurred at different times in a cycle (normally 30) and the average and oscillating burning rate during a cycle were determined at several (normally 30) different axial locations. For this study, calculations were made for injection only at the median area (0.7 rad.) position and one angular position to represent the entire injector face.

The theory of Ref. 3 was modified to include finite thermal conductivity by calculating the heat transfer between shells within each drop. The influence of liquid circulation was approximated by only using 4 shells to simulate a more gradual temperature profile obtained with circulation. The stability calculations are sensitive to the number of shells used (up to a limit of 50) and/or the thermal conductivity.

To account for combustion in the critical region, where the surface temperature exceeds critical temperature, the heat of vaporization was assigned 0.001 Btu/lb at temperatures above the critical temperature, but the vapor pressure was permitted to vary as the surface temperature changed. Therefore the calculations determined a pseudo surface where the pressure of the vaporizing fluid is equal to the calculated vapor pressure. All other properties were taken from Ref. 3 and assumed to remain constant during the lifetime of the drops.

The influence of injection on atomization was included by the variation of drop size and velocity as a function of time as calculated by atomization theory. The influence of the gas oscillations were included by using the local pressures and velocities produced by the gas oscillations as a function of time. A noise velocity was also added to the velocity by assuming that a root mean square pressure oscillation of 1.5 percent chamber pressure was present.

WAVE DYNAMICS

Gas phase oscillations in the chamber were calculated using distributed combustion (over 30 positions) and the wave equation with the separation of variables assumption.[4] Between the axial stations the oscillation profiles were calculated via the wave equation with a finite velocity gas. At the various axial positions the average velocity and oscillating velocity were changed on the basis of the average burning rate for that area and the oscillating burning rate. This required an iterative solution approach to obtain the same burning rates from the vaporization equations as that used in the wave dynamics equation. The calculations for wave dynamics started at the nozzle and proceeded to the injector with an assumed average burning rate response. If the velocity at the

injector face was not zero, a new average burning rate response was assumed. The calculations were repeated with different frequencies (actual frequency and damping rate) until the average burning rate response (in phase and out of phase components) agreed with the vaporization rate calculations.

For the wave dynamics the local speed of sound was allowed to vary as a function of axial position (as noted in Ref. 1) based on the amount of burning that had occurred at that position. For simplicity, the oscillations at the nozzle end of the chamber were assumed to follow the laws for an ideal, short-distributed nozzle.

RESULTS

SAMPLE CALCULATIONS

To illustrate the models capability, sample calculations were made to demonstrate the importance of different terms. The calculations used the design and operating parameters for the 40 K LOX Methane engine as shown in Tables I and II.

(Other design and operating parameters can be found in Refs. 1 and 5.) For these calculations the operating conditions were those of the unstable engine at an O/F of 2.55 with an oscillating frequency of 4163 Hz and a half amplitude of 151 psi at the injector face.

An important result is the drop history, which is shown in Fig. 1 for the mass median drop size injected when the pressure is at nominal and increasing. The drop mass (Mdrop) decreases smoothly to zero in 4-1/2 periods of oscillations. The surface temperature (Tdrop) rises rapidly to about 340 °R in 1/6 of a period and then varies by 10° with the pressure oscillation. The temperatures of the inside three shells remained constant within 1° until the drop was 99 percent vaporized. The vapor pressure at the surface temperature (Pvap) is always within 0.1 percent of the chamber pressure, and has a slight lag.

The heat transfer to the drop (Qdrop) starts very high and drops as the temperature (vapor pressure) and vaporization rate increase. When the drop surface temperature is above 330 °R, the bulk of the heat transfer is being carried away by the heat required to raise the temperature of the vaporizing mass. After the drop reaches 340°, the heat transfer oscillates and at times approaches zero (when the vaporization rate is maximum). The vaporization rate (W) rises rapidly initially as the drop heats up and then decreases as the drop size decreases. The vaporization rate has an oscillation that is very nonlinear. The maximum rate in a period occurs just after the pressure is maximum. The minimum rate occurs just prior to the maximum pressure. Many drop histories are used to describe the burning in an engine, all of which are different due to the drop size and drop injection time.

The variation in drop conditions with injection time is shown in Fig. 2. For this calculation, 30 different injection times were used. The fuel and LOX velocity are shown along with mean drop size, and the distance required to vaporize 50 percent of the mean drop. Because of the influence of velocity on drop size, the mean drop size varies by about 20 μm (10 percent) and is out of phase with the fuel velocity (the smallest drops occur when the fuel velocity is highest). The drop size has a wiggle in it because some of the drops are being formed in the chamber and are influenced by the local gas oscillations. The distance required to atomize 50 percent of the jet was always within the recess, so the atomization plane is at the injector face. The distance required to vaporize 50 percent of the mean drop varies between 0.125 and 0.175 in. The longest distance occurs when the drops are small because the gas oscillation environment that the drop sees is more important than the size. By comparison, during steady state the distance for 50 percent vaporized is 0.27 in.

Nonlinear aspects of the theory and calculations are illustrated in Fig. 3 for various responses. The combustion response is shown along with the response needed in the chamber to satisfy the gas oscillation equations. The chamber response decreases slightly with amplitude from 3.65 to 3.45 while the vaporization results show a dramatic change in the combustion response from 4.0 to 1.0 at high amplitudes.

The LOX injection response is reasonably constant at low amplitudes. At 450 psi amplitude a pressure below the saturation pressure of LOX is reached at a location 1/2 in. downstream of the orfice. A square root law to decrease the response with increasing amplitude was used in the calculations to decrease the response to approximate what might happen when saturation and two phase flow is occurring in the injector element at higher amplitudes. The LOX dome, fuel injector, and fuel dome responses all remained relatively constant.

The influence of frequency on the calculations is shown in Fig. 4. As the frequency varies from 3500 to 5500 Hz, the amplitude of the combustion response only varies between 3.2 to 4.2 while the chamber response varies between 0.8 to 5.0. Similarly, the LOX injector and dome responses vary significantly as the systems "tune." The characteristics with frequency are opposite to those with amplitude.

In the results presented above, either frequency or amplitude was chosen as the only independent variable. In a combustor these variables both change as shown in Fig. 5. For this calculation the frequency was allowed to change with amplitude until the combustion response agreed with the response used in the chamber to determine the gas oscillations. The combustion and chamber response vary from 5.6 to 0.8 as the amplitude increases from 100 to 1000 psi. Above this pressure, everything remains relatively constant. The LOX injector response reaches a maximum at about 150 psi where it is tuning with the 4200 Hz oscillation.

COMPARISONS WITH TEST DATA

As a first attempt to validate the model, calculations were performed at conditions representing those reported in Ref. 1 for the LOX Methane Engine and Tables I and II. To accomplish this, the constants in the Mayer atomization equations were determined using the steady state performance at full thrust assuming a 98 percent mixing efficiency. Values of 35,500 for the drop size constant and 15 for the atomization rate constant were obtained when the oxidizer is allowed to fully expand in the chamfer. Lower performance with prestage combustion (when the chamber pressure was lower) indicated that the flow was separating during prestage conditions.

Results for stable and unstable test conditions (tests 0012 and 0019) respectively are shown in Fig. 6. Frequency and damping rate (real and imaginary part of the calculated frequency) are shown in Fig. 6 as a function of amplitude at the injector end of the chamber. At 100 psi amplitude the frequencies of both engines are about 3450 Hz and they rise rapidly with amplitude, reaching 5000 Hz range at an amplitude of 500 psi. Both level off, at a frequency of 5000 Hz for the stable engine condition and 5200 Hz for the unstable.

The damping rate (rate at which a wave will decay in amplitude if positive, or grow if negative) is also shown in Fig. 6. The unstable engine condition has a positive damping rate until an amplitude of 135 psi (with a frequency of 4100 Hz) is reached and then becomes negative (unstable). A wave with a negative 600 1/sec damping rate (with frequencies between 4000 and 5000 Hz) will double in amplitude every millisecond or grow to 1040 psi in 3 msec.

The stable engine calculations show that the engine is stable until an amplitude of 280 psi is reached and then becomes almost as unstable as the unstable engine. The frequency at 280 psi for the stable engine is around 4500 Hz.

The instabilities quoted for this engine in Ref. 1 had "low amplitude modes....exponential growth would occur over a period of from 5 to 10 msec with growth rates in the range of 500 1/sec. In all cases the oscillation would take multiple cycles to grow in amplitude and shift in frequency from near 4 to 5 kHz." (See Fig. 48 of Ref. 1 for more detail). High frequency chamber pressure data were not obtained for these tests so it is impossible to compare chamber pressure amplitude results. The experimental peak to peak amplitudes in the LOX and fuel dome prior to the onset of instability were 70 to 80 psi. The calculated dome pressures for a frequency between 4000 and 4200 Hz and a chamber pressure half amplitude of 151 psi was 30 to 40 psi peak to peak for the LOX and 100 to 300 psi for the fuel.

Considering the accuracy in obtaining high frequency pressure data, location of transducers and the ability to absolutely model pressure profiles in the feed system hydraulics, this is considered to be good agreement between experimental and calculated amplitudes. The frequency shift with amplitude is in excellent agreement. The quoted test growth rate of 500/sec is also very close to the calculated growth rate which varies from 600 to 300/sec.

The presence of a negative damping rate at high amplitudes for "stable engine operating conditions" would infer that the engine could be bombed unstable at this condition if a wave with 500 psi amplitude was produced. The engine was bombed at mixture ratios of 3.18, 3.38 and went unstable. A bomb test at 3.69 was stable. The amplitude of the bomb disturbance was 1080 which produced a 1T mode (5000 to 5200 Hz) oscillations. The amplitude of the oscillation, after the bomb, decayed to about 300 psi pk. to pk. (150 psi amplitude). Thus the engine is predicted to be close to an instability with the bomb at the stable mixture ratio of 3.48 and lower mixture ratios should definitely bomb unstable.

Calculations were made for other modes in the chamber to determine if they would be expected to be more stable. All of them were more stable (requiring a higher amplitude to initiate an instability). A summary of the calculations are shown in Table III giving the frequency and amplitude to initiate instability at the unstable operating conditions. No solutions for higher frequency combined longitudinal-transverse modes were found.

The LOX Methane engine also exhibited a higher frequency (14,000 Hz) oscillation when the temperature of the Methane was reduced to 440 °R. at a mixture ratio around 3.1. Calculations were

performed for these operating conditions and different mode numbers (several modes involving the radial and transverse components are expected to produce oscillations near 14 kHz). The results of these calculations are shown in Table IV.

These results show that at lower temperatures the engine becomes more unstable for higher order modes and the 4200 Hz mode becomes more stable. This indicates a 14 kHz oscillation condition does exist when the Methane temperature is reduced to 440 °R and that the mode number does influence the stability results. All of the modes exhibited similar amplitudes required to initiate an instability. The higher frequency oscillations with the 3T-OR or 4T-OR modes had higher maximum growth rates and lower initiation amplitudes, therefore they would predominate and be the most unstable conditions as observed.

The 1T-1R mode has a unique feature in the calculations. For this mode the amplitude at the 0.7 radial position (for which the calculations were performed) has an amplitude of 0.1 of that at the wall. Also the radial velocity is two orders of magnitude larger than the value used for other modes. The influence of using different radial positions to represent this mode was not investigated.

The LOX Methane engine has also shown that injector design changes influence the stability. A test (004) with a higher chamfer angle (and longer tube) resulted in a 5 kHz oscillation at a mixture ratio of 3.1. This test also had a much lower performance (92 percent versus 96 to 98 for other tests). Therefore it was assumed that the flow in the chamfer was 80 percent expanded (which resulted in a calculated performance of 92.5 percent). The stability calculation for these conditions showed that the engine is unstable above an amplitude of 280 psi. This amplitude is equal to the level required for the nominal design at a similar operating condition. This indicates a definite possibility of producing an instability. Test 004 was the first full duration firing of the engine. The starting sequence was changed after test 004 to obtain a smoother and more reliable start. Therefore test 004 could have had a higher initial disturbance, similar to the bombs which produced instabilities at the same test conditions.

Another version of the LOX Methane engine (called MSFC design in Ref. 5 and Tables I and II) has been tested extensively without encountering an instability. The MSFC design has different lengths for the LOX and Fuel tubes as shown in Table I. These design changes would be expected to change the response of the fuel and oxidizer systems. Calculated results for the two engines at the unstable operating conditions with an amplitude of 141 psi and at instability conditions are shown in Table V.

This data shows that changes in dimensions do influence the responses of the engine and can result in a much more stable engine. The changes in the LOX and Fuel tube dimensions and less flow through the element due to face cooling with the MSFC design results in a higher amplitude required to initiate an instability and a change in frequency for the expected oscillation. The calculations show that the MSFC design is a more stable engine as observed experimentally. This helps validate the models ability to predict the influence of injector design changes on performance and stability.

CONCLUSIONS

Calculations using the nonlinear model described herein agreed (using experimental data to anchor the coefficients) with the experimental nonlinear stability characteristic of a 40 K LOX Methane engine involving:

1. The amplitude of the oscillation required to initiate instabilities spontaneously or with a bomb.

2. Growth (or decay) rate of the instability.

3. Frequency change with amplitude of an instability or fuel temperature.

4. Engine operating conditions like Mixture Ratio and Fuel temperature.

5. Injector design variables that change the tuning of the injector and flow.

The model includes the major nonlinear features involved in the injection, atomization and vaporization processes. Wave dynamics is modeled using the separation of variables approximation so variations in combustion rate oscillations in the radial and tangential directions were neglected and approximated by an average assumed to be at the 0.7 radial position. An improvement to the model can be made by solving for the full three-dimensional wave dynamics with variable combustion rate oscillations in the radial and tangential directions. This would also permit calculating the interaction of baffles and absorbers with the combustion process to control instabilities.

REFERENCES

1. Jensen, R.J.; Dodson, H.C.; and Claflin, S.E.: LOX/Hydrocabron Combustion Instability Investigation. NASA CR-182249, 1989.

2. Mayer, E.: Theory of Liquid Atomization in High Velocity Gas Streams. ARS Journal. vol. 31, no. 12, Dec. 1961, pp. 1783-1785.

3. Priem, R.J.; and Heidmann, M.F.: Propellant Vaporization as a Design Criterion for Rocket-Engine Combustion Chambers. NASA TR R-67, 1960.

4. Maslen, S.H.; and Moore, F.K.: On Strong Transverse Waves Without Shocks in A Circular Cylinder. J. Aeronaut. Sci., vol. 23, no. 6, June 1956, pp. 583-593.

5. Priem, R.J.; and Breisacher, K.J.: Combustion Instability Coupling with Feed System Acoustics. Advanced Earth-to-Orbit Propulsion Technology 1988, vol. 1, R.J. Richmond and S.T. Wu, eds., NASA CP-3012-VOL-1, 1988, pp. 270-301.

TABLE I. - DESIGN FEATURES OF METHANE LOX ENGINES

Parameter	Standard Lewis	Original Lewis	MSFC
Chamber diameters, in.	5.66	5.66	5.66
Nozzle diameter, in.	3.31	3.31	3.31
Chamber equivalent cylindrical length, in.	11.38	11.38	11.38
Exit diameter of LOX tube, in.	0.136	0.136	0.136
Chamfer angle of LOX tube, deg	6	15	6
Length of LOX tube, in.	3.66	3.66	4.68
LOX orfice diameter, in.	0.086	0.086	0.086
LOX dome diameter, in.	6.5	6.5	6.5
LOX dome equivalent length, in.	1.12	1.12	1.12
Fuel annulus i.d., in.	0.202	0.202	0.202
Fuel exit annulus o.d., in.	0.224	0.224	0.224
Fuel exit annulus length, in.	0.40	0.40	0.63
Fuel orfice annulus o.d., in.	0.215	0.215	0.215
Fuel entrance annulus length, in.	0.73	0.73	0.73
Fuel dome diameter, in.	6.0	6.0	6.0
Fuel dome equivalent length, in.	2.225	2.225	2.225
Element recess, in.	0.2	0.2	0.2

TABLE II. - OPERATING CONDITIONS OF LOX METHANE ENGINE

Parameter	Lewis stable test 012	Lewis unstable test 019	MSFC
Engine O/F	3.48	2.55	2.55
Chamber pressure, psi	1980	1886	1886
Combustion temperature, °R	6560	5972	5972
Gas speed of sound, in./sec	51 819	51 787	51 787
Gamma	1.182	1.182	1.182
LOX flow, lb/sec	68.96	61.74	61.74
LOX temperature, °R	211	216	216
LOX speed of sound, °R	31 222	30 219	30 219
Fuel flow[a], (element), lb/sec	19.18	24.23	21.19
Density of fuel, lb/in.^{3}	0.00523	0.00527	0.00527
Fuel speed of sound, in./sec	18 644	18 576	18 576

[a]Element fuel flow for the MSFC engine is reduced due to the flow going through the rigimesh face cooling.

TABLE III. - STABILITY OF HIGHER ORDER MODES

Mode,	Initiation amplitude, psi	Frequency, Hz
2T	405	8 525
3T	538	11 596
4T	436	14 613
5T	625	18 219

TABLE IV. - OSCILLATION CHARACTERISTICS AT LOW METHANE TEMPERATURE

[Amplitude of calculation, 141 psi.]

Mode	Eigen-value	Initiation		Maximum growth rate 1/sec
		Amplitude, psi	Frequency, Hz	
1T-1R	5.33	483	11 031	2016
3T-0R	4.2	317	13 958	3297
4T-0R	5.32	294	13 868	3058
1T-0R	1.84	169	4 234	708

TABLE V. - COMPARISON OF STABILITY CHARACTERISTICS FOR LEWIS AND MSFC DESIGN

	Lewis		MSFC	
Fuel velocity response at 4000 Hz	-0.220	-0.012	-0.202	-0.011
LOX velocity response at 4000 Hz	-0.048	-0.008	-0.004	+0.008
Combustion response at 4000 Hz	-0.924	-3.710	-0.843	-4.300
Chamber response at 4000 Hz	-0.659	-4.030	-0.720	-4.230
[a]Calculated C efficiency (98 percent mixing)	98		97.9	
Instability point:				
Amplitude	128		396	
Frequency	3956		4904	
Maximum growth	1048		816	

[a]Responses are given in real and imaginary values for complex notation or in-phase and out-phase values in Sine - Cosine notation.

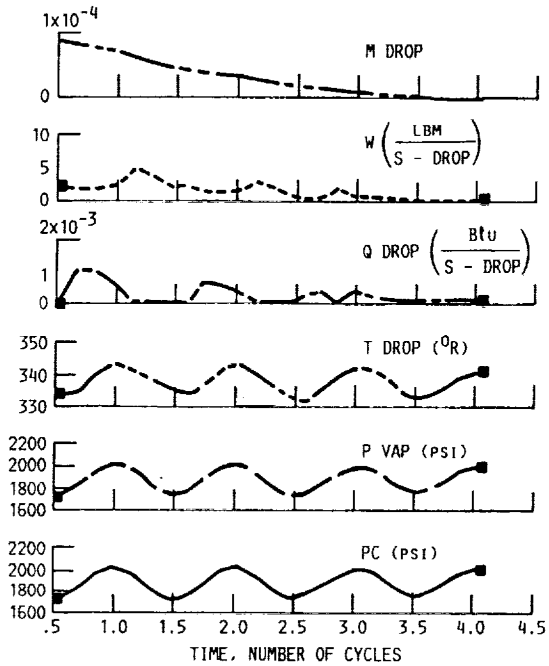

FIGURE 1. - DROP VAPORIZATION HISTORIES FOR THE MEAN DROP.

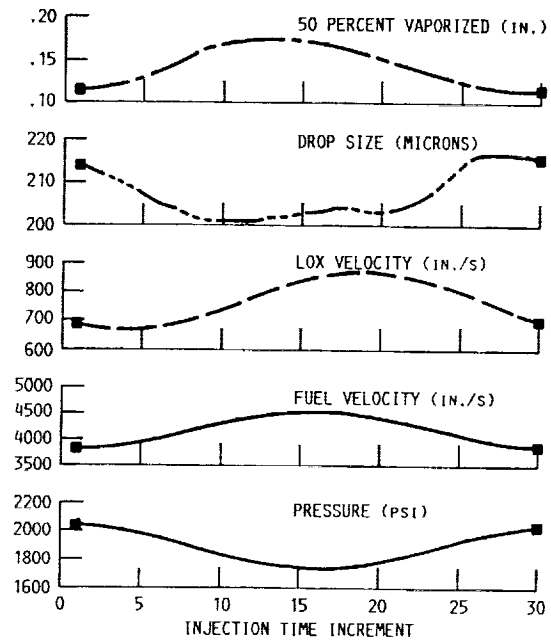

FIGURE 2. - INFLUENCE OF INJECTION TIME ON DROP CHARACTERISTICS.

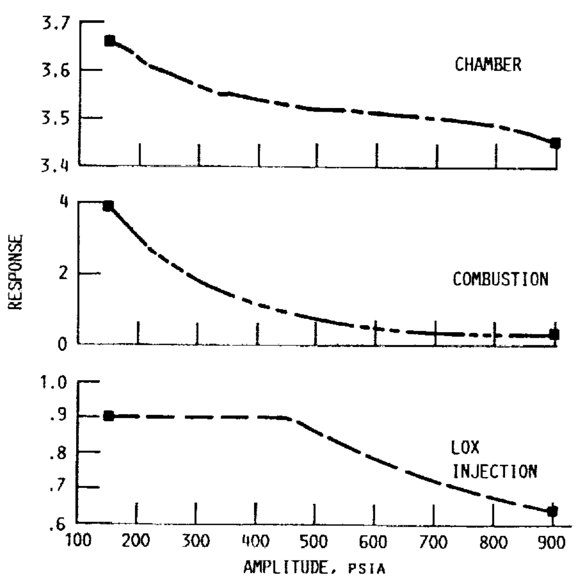

FIGURE 3. - INFLUENCE OF OSCILLATION AMPLITUDES ON RESPONSES.

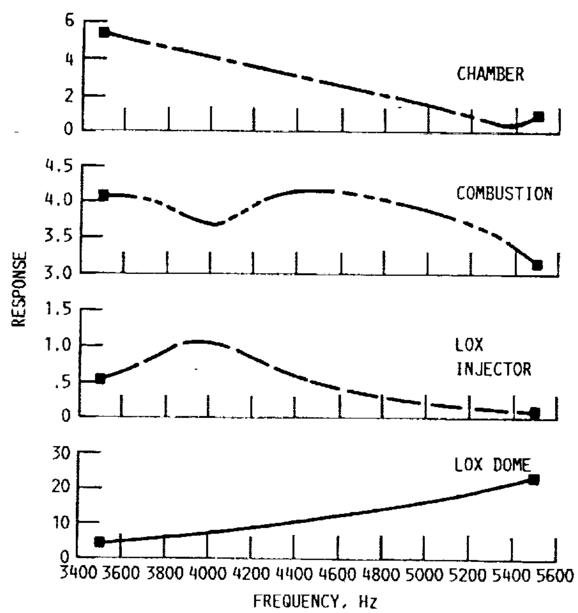

FIGURE 4. - VARIATION OF RESPONSES WITH OSCILLATION FREQUENCY.

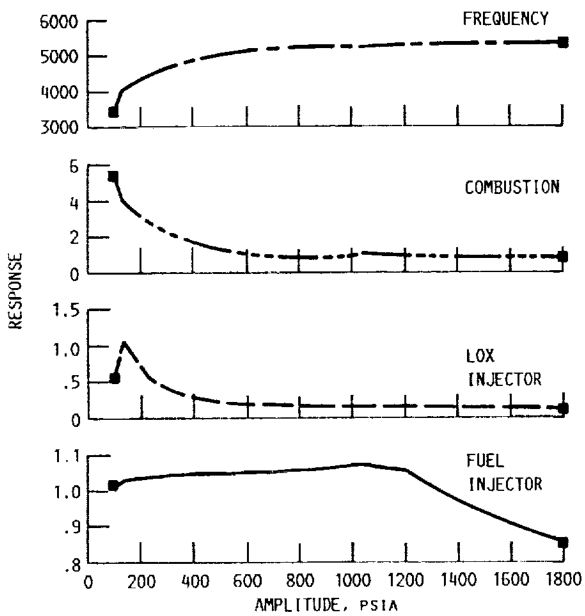

FIGURE 5. - NONLINEAR CHARACTERISTICS OF 40 K LOX/ METHANE ENGINE RESPONSES.

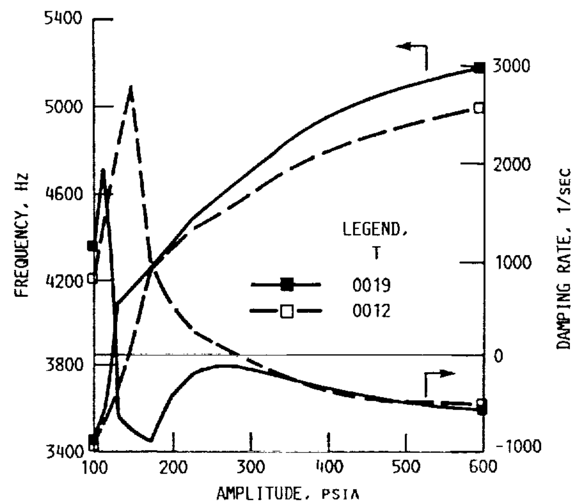

FIGURE 6. - 40 K LOX/METHANE ENGINE STABILITY CHARACTERISTICS.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-102381	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Nonlinear Combustion Instability Model in Two- to Three-Dimensions		5. Report Date 6. Performing Organization Code
7. Author(s) Richard J. Priem and Kevin J. Breisacher		8. Performing Organization Report No. E-5097 10. Work Unit No. 582-01-21
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No. 13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 26th JANNAF Combustion Meeting, Pasadena, California, October 23-27, 1989. Richard J. Priem, Priem Consultants, Inc., 13533 Mohawk Trail, Cleveland, Ohio 44130; Kevin J. Breisacher, NASA Lewis Research Center.

16. Abstract

A model is developed based on using "quasi-steady state" equations for the injection, atomization and vaporization processes that consider the instantaneous local pressures, temperatures, density and gas velocity vector associated with a three-dimensional wave. The coupled sets of equations are solved to determine frequency and growth rate of the oscillations as a function of wave amplitude. Calculated results are used to explain the observed instabilities in a 40 Klb LOX/Methane combustor.

17. Key Words (Suggested by Author(s))

Combustion instability
Feed system
Methane

18. Distribution Statement

Date for general release October 1991.
Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	10	A02

NASA FORM 1626 OCT 86